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LEVERAGING FOURTH INDUSTRIAL REVOLUTION TECHNOLOGIES AND DESIGNS FOR REALISING ENERGY EFFICIENCY AND ENERGY SECURITY IN DEVELOPING COUNTRIES

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ABSTRACT

The human capacity challenges faced by developing countries regarding energy efficiency and energy security projects will take longer in comparison to obtaining financing and unfortunately cannot be developed overnight. Depending on the extent of the implementation of new technologies (within a specific organisation or the national energy generation scheme of a developing country), changing to technologies that are new to the operating environment may pose a hurdle to implementation due to the business, safety or operational risks that the technical unknowns may present. Another challenge with renewable energy is its intermittency and space requirements which call for energy storage and land availability. Energy storage technology, although has made significant progress requires greater efficiency for attractive payback periods. This makes many renewable energy projects unfeasible. Renewable energy is unlikely to be adopted on a large scale due to it not being able to efficiently serve customers' needs. Energy demand naturally has peaks and troughs according to human and economic activities and requiring a baseload energy capacity, which makes energy generation a challenging and costly task, especially with renewable energy. These challenges can be speeded up through innovative thinking and the use of instruments arising from the fourth industrial revolution. This paper presents an approach to leveraging the instruments of the fourth industrial revolution to overcome the challenges faced by developing countries in adopting energy efficiency and making provisions for their energy security.

KEYWORDS: Fourth Industrial Revolution and Energy Efficiency, Smart Electrical Grid and Renewable Energy, Load Curtailment Programmes & Smart Control Systems

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Original Article

INTRODUCTION

Industrial revolutions change the way we live through technological advancements and innovation (Fig. 1). Each industrial revolution brings benefits and challenges to the countries that have engaged in such transformation [1]. Great Britain led the first industrial revolution with the invention of the steam engine, which revolutionised communication and transportation and led to many other industrial developments [1]. In the second industrial revolution, the United States led with the telephone which revolutionised communication. In the third industrial revolution, the internet was the key factor and succeeded because it was conceived of as a public infrastructure technology rather than a proprietary technology [1]. The internet transformed the world economic landscape, and this is being carried forward with the internet of things (IoT) [1]. Industry 4.0 is not an exception to the previous eras of industries; it is expected to bring immense benefits and many challenges, the main one being the cybersecurity risk [1]. Industry 4.0 is characterised by what is called the "smart factory" [1]. In a smart factory, a virtual copy of the physical world and decentralised decision making can be developed, physical systems can

communicate with each other and with humans in real time, all enabled by the IoT and related services [1].

Industry 4.0, which started in Germany, is being adopted by countries around the world including the USA, France and Japan which have already taken the first step in this direction by launching nation-wide programmes [2]. With the increased use of digital technologies, the boundary between the real and the virtual world is increasingly blurred, giving rise to what is known as cyber-physical production systems (figure 2) [2].

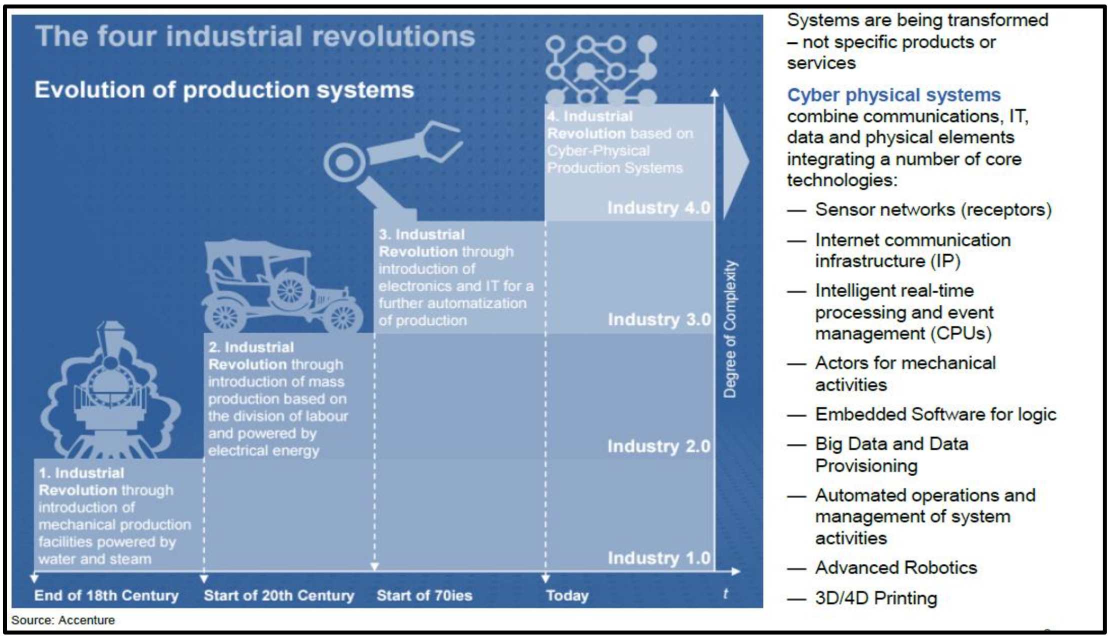


Figure 1: The Four Industrial Revolutions [3].

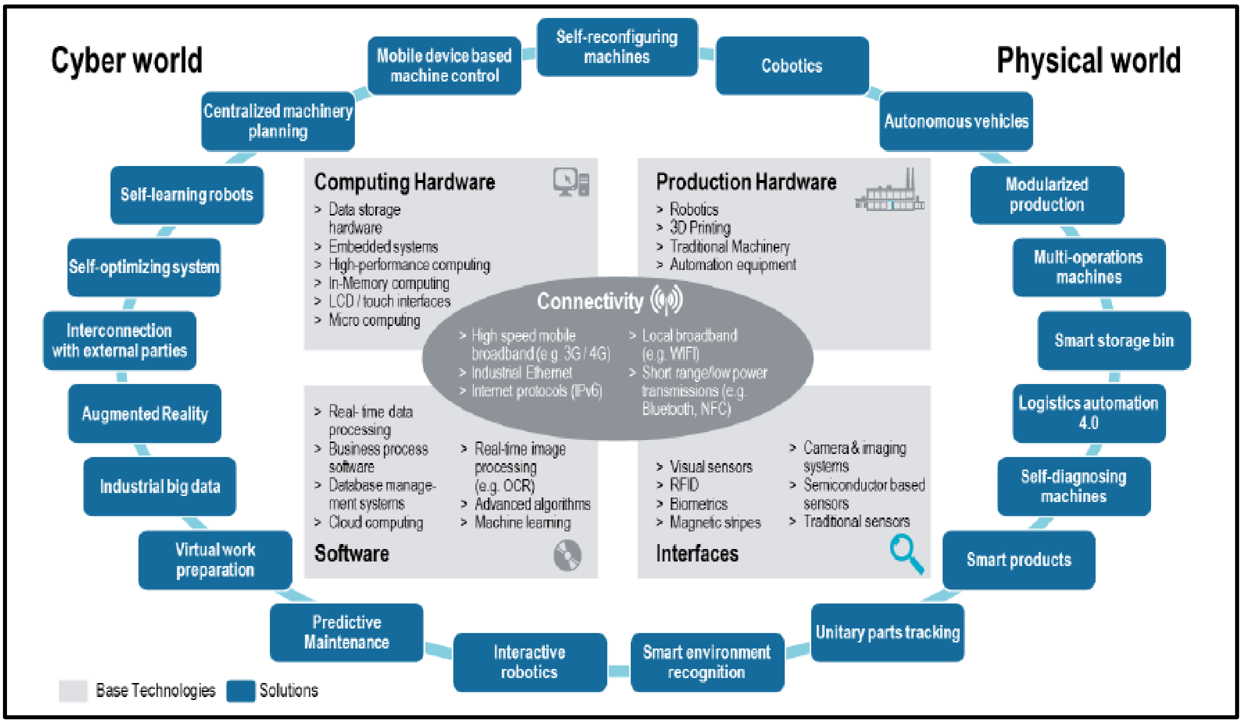
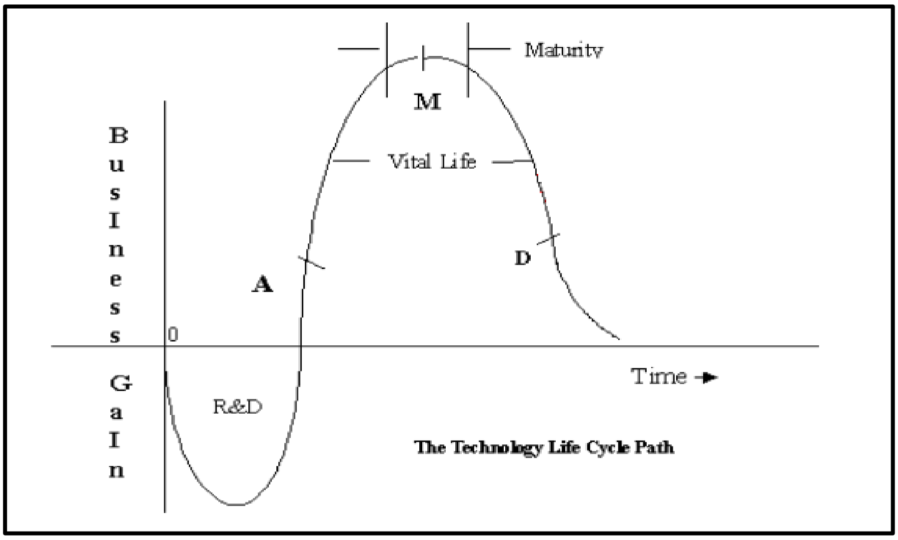


Figure 2: Potential Industry 4.0 Solutions [2].

The capacity to store, process and provide real time control of engineering systems based on artificial intelligence (AI) algorithms has been an industry-changing moment for the world. The full potential of AI and its applications has not yet been fully exploited and its applications are limitless. However, AI in the context of employment and socioeconomic challenges are regarded in some quarters as being a disadvantage because it makes certain careers obsolete and requires that the workforce be trained to use the technology. This paper discusses specific opportunities that the technologies of the fourth industrial revolution provide for energy efficiency and energy security in developing countries.

Most of the barriers faced by developing countries stem from the nature of the life cycle of technology (Figure. 3). Current fossil fuel generation technology such as coal-fired power plants have been around for at least 100 years and therefore this is a mature technology. There is a lot of business gain with such technology as indicated in the graph in Figure 3. Figure 4 shows the market saturation curve in relation to the technology life cycle development. Competition is great towards the latter part of the technology generation curve and the prime time for developing countries to adopt the technology at a low price, meeting their affordability, and over time building technical capability.



Note: A = Ascent phase, M = Maturity stage, D = Decline (or Decay) Stage
Figure 3: The Technology Life Cycle Path (Adapted from [4]).

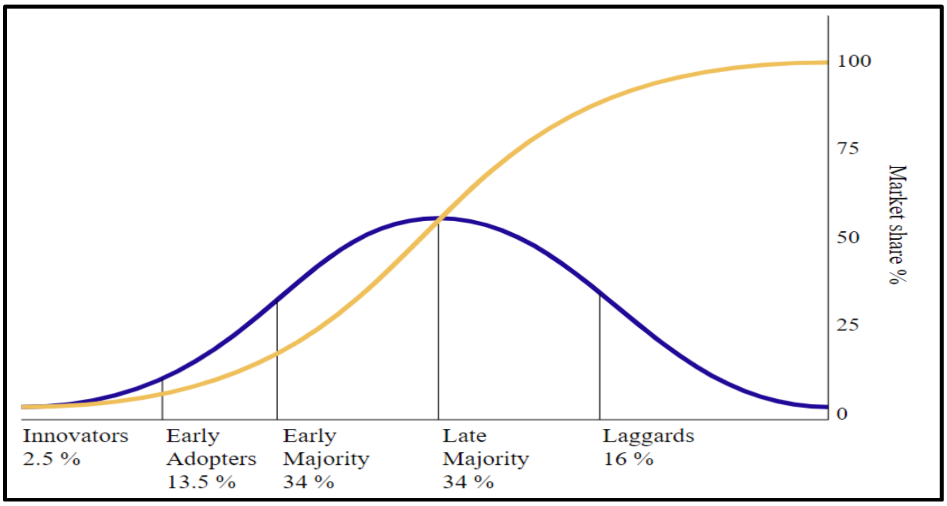


Figure 4: Technology Life Cycle Bell Curve (Blue) and Market Saturation Curve (Yellow) [4].

Developing countries are on a budget in that they look for goods and services at the lowest possible first cost especially regarding access to energy that is key for economic development and the betterment of the lives of its citizens. Thinking long term in the context of sustainability and adoption of new technologies that come with the research and development costs (R&D), as indicated in figure 3, is not a priority when competing concerns of access to clean water, housing, medical care, food and jobs are immediate needs.

This is not necessarily a negative characteristic of developing countries, but what this type of behaviour does in the long term is that it leads to the developing countries always playing "catch up" when it comes to technology adoption and inevitably, therefore, lag in economic growth in relation to developed countries. There is a need to take a different view that does not ignore developing countries' immediate needs and dynamics but looks at the potential of the move to sustainability as a market opportunity to generate the change needed to swing economic favour in the direction of developing countries at the same time as providing the much needed revenue for the immediate needs of the country.

Innovation is key to economic development. The fourth industrial revolution with cyber-physical systems and AI presents major opportunities for developing countries to leapfrog the barriers faced in transitioning towards energy efficiency and energy security. The following sections present solutions that leverage off the fourth industrial revolution to establish and sustain the move of developing countries towards energy efficiency and energy security.

One of the barriers faced by developing countries to achieve energy efficiency and energy security lies in the capacity of the workforce that is required to operate and maintain the technologies for an alternative low carbon energy mix. The capacitating of the local workforce is part of the journey that developing countries must make and this could be the limiting factor preventing them from realising a low carbon energy mix. Many times, those developing countries that progress well with climate change mitigation make use of a significant portion of foreign labour. While this is good in the context of climate change, it is not sustainable from a socio-economic perspective. It takes a certain amount of time for the local workforce to be trained and competent in operating and maintaining new technologies. Technologies that are emerging in this fourth industrial revolution phase that utilise AI can be designed to transition developing countries utilizing low carbon energy generation technologies by intelligently operating itself and providing detailed information that will assist trouble shooting and maintenance.

At some point in time, however, developing countries must have a local workforce that understands the engineering technologies in detail so that design and manufacturing can be done locally which will involve knowledge and skills transfer of technologies designed by other countries. Computer simulations can assist with knowledge transfer and training for competence and the virtual work environment can effectively lower the cost of foreign consulting and expertise.

An energy mix on its own is not sufficient – there must also be coordination of renewable and alternative energy sources according to availability, cost and other business imperatives to ensure that the site's energy demand is satisfied efficiently and without interruptions. Computer algorithms and programable logic controllers (PLCs) can coordinate energy sources in a smart electrical grid as well as engineer the energy demand for the most efficient energy supply and demand matching.

1. Artificial Intelligence for Maintenance, Operations and Trouble Shooting

AI involves a computer system performing as a substitute for intelligent functions of human beings [5]. In this case, a

computer system performing troubleshooting for maintenance, providing key indicators that inform predictive maintenance and operations of the plant. AI computer systems mimic the methods of learning and solving problems by human beings through knowledge gathering [5]. AI includes the following areas of activities [5]:

- Processing of human language
- Image processing
- Intelligent robots
- Expert systems
- Neural networks

These systems have the knowledge of experts and can make a diagnosis of any abnormality of a given piece of equipment [5]. Time-based preventive maintenance has been used as a basic method; increasingly condition-based maintenance is being introduced in many working environments [5]. Diagnostic techniques based on machine condition are used to detect degradation of plant equipment [5]. In Japan, these techniques have been known since the 1960s in the steel manufacturing industry [5]. The following are some examples [5]:

Machinery and Equipment [5]

- Fluid machines
- Electric rotation machines
- Mills
- Stationary electric machines
- Motors
- Blowers
- Pumps
- Towers
- Drums

Sensing Place [5]

- Bearing portions
- Tanks
- Shafts
- Pipes

Many expert systems for diagnosis were developed by maintenance engineers, and software tools have been introduced in the United States and reconstructed in Japan [5]. An expert system contains a knowledge base and an inference engine [5]. The knowledge required for the diagnosis is expressed by production rules or frame representations

[5]. The basic structure of an expert system is given in figure 5 [5].

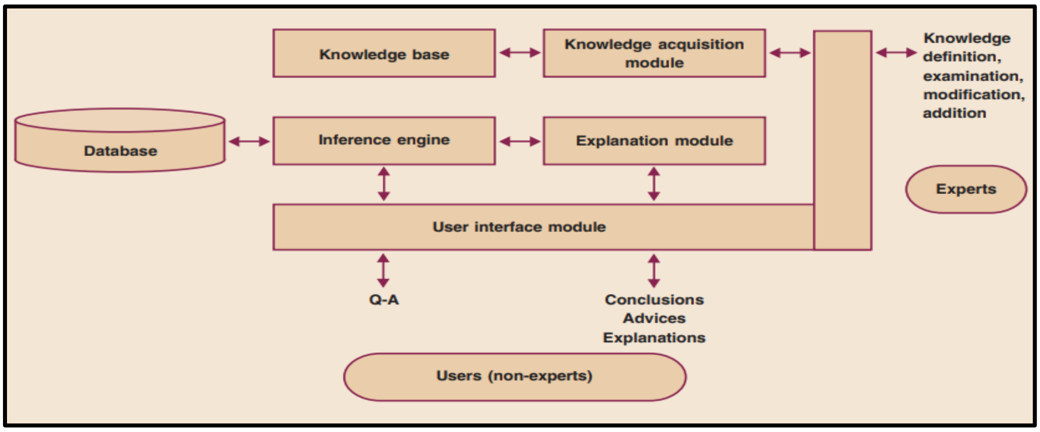


Figure 5: Overview of an Expert System [5].

“Based on given information of the apparatus, the inference engine works to obtain conclusions and give advice” [5]. The application of AI for the operations, maintenance and troubleshooting for renewable energy and alternative energy technologies are already available commercially. Solar photovoltaic (PV) plants can be designed with an intelligent control system having a SCADA (supervisory control and data acquisition) interface for real-time operational control. Further programming and neural networking are also possible on solar PV plants to provide alerts for maintenance and in some cases also perform maintenance such as washing of panels via robots. Troubleshooting for effective corrective action to be executed is also achievable with neural networking, sensors and databases providing the platforms for artificial intelligence.

Alternative energy such as natural gas trigeneration plants, anaerobic digestion plants, renewable energy such as solar thermal, solar PV, wind energy, geothermal energy, are novel sources of energy being adopted by sites like airports in South Africa [6], [7], [8], [9], [10], [11]. In these settings, AI can reduce the cost of operations and maintenance as well as downtime through troubleshooting. Furthermore, AI provides a means for closing the immediate skills gap by allowing the local workforce to learn about the operations and maintenance of the system through the record keeping database of the system.

Regarding the adoption of renewable and alternative energy technologies at airports in South Africa [6], [7], [8], [9], [10], [11], it is advised that AI be used in relation to:

- Solar photovoltaic power plants
- Solar thermal absorption cooling plants
- Natural gas trigeneration power plants
- Geothermal heat sink plants
- Anaerobic digestion power plants
- Vertical axis turbine wind powerplants

AI should be used to provide a real-time “heartbeat” of each powerplant and store data in a cloud-based system.

This data should be accessible by the plant designers for the first 18-24 months via a web-link so that plant operational glitches and AI bugs can be resolved remotely as well operational parameters be refined to suit the operating environment. It is crucial that during this period a selected number of suitably qualified engineering personnel from the plant owner become familiar with, and if necessary be trained on the technologies and their operations, so that they can become familiar with troubleshooting and undertaking maintenance tasks. A computer programmer selected by the plant owner should be included in the project for the first 18-24 months which will position the plant owner to be able to insource all operations and maintenance in due course.

It is advised that sensors and neural networks be arranged around the:

- Maintainable components
- Components and plant aspects that can fail which can then cause plant failure
- Parameters that must be monitored for optimal operations
- Parameters that must be controlled for daily plant operations
- Components and plant that will be used daily for quality checks
- Records of daily activity on plant, SCADA and web-based systems

After this period, it may be that the need for an onsite operations and maintenance team and the need for outsourcing these services be assessed against the cost of renewal of software licences, sensors and hardware of neural networks and auxiliary systems. Based on cost, efficiency, market availability and maturity and other business imperatives, the plant owner may decide to reduce the neural network coverage and outsource the operations and maintenance or retain the AI component and perform inhouse maintenance and operations or even reduce the AI component depending on the business risk and technology complexity versus the demand for personnel.

This AI approach to close the skills gap for organisations will reduce the anxiety and address many business risks related to operations, maintenance, troubleshooting for efficient, reliable and uninterrupted energy supply from a low carbon energy mix.

2. The Value of Computer Simulation as a Tool for Learning about New Engineering Technologies

In order for developing countries to transition to a low carbon energy supply, capacity needs to be built to understand and design low carbon and renewable energy power generation technologies and develop competence from manufacturing to operation and maintenance. Before the fourth industrial revolution, design of the technologies relied on universities, methods of learning the operation of new technologies relied on person-to-person knowledge transfer, and maintenance relied solely on technical training. Although quite thorough, these methods required costly investments and usually, proprietary information was a barrier to plant owners becoming independent of original equipment manufacturers (OEM) and plant designers. This arrangement still exists in South Africa with many technologies, especially those that have specialised SCADA interfaces. This has major disadvantages to plant owners starting with exorbitant costs and extensive business risks due to consultants being overseas and mostly person-dependant.

Computer simulation that details the working of various renewable and alternative power generation technologies can bring easy access to technology familiarisation. A computer simulation is a programme that contains a model of a

system, natural or artificial, of equipment or a process [12]. A computer simulation accepts inputs, incorporates those inputs into calculations or modelling, and presents functional outputs [13]. By actively involving learners in exploring and discovering, computer simulations are powerful learning tools, as learning that involves doing is retained for longer than learning via listening, reading, or seeing [12]. Computer simulation of engineering work focuses on the design of products and processes to meet social needs. Virtual laboratories that focus on engineering practice can centre on design [14]. The design process is built around iteration, where a design idea is improved based on the identified shortcomings of previous attempts [14]. Identified shortcomings allow a feedback cycle where the designers can identify gaps in their knowledge and understanding, providing impetus for further learning [14]. For engineering professionals, this practice of knowledge building through iterative design cycles is critical [14]. Figure. 6 shows the process of building a computer model and the interplay between experiment, simulation and theory.

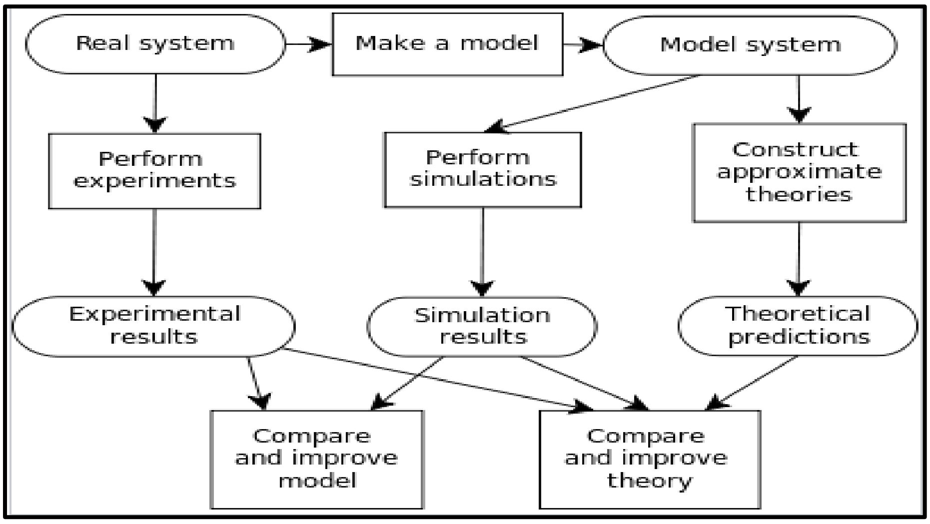


Figure 6: Process of Building a Computer Model and the Interplay between Experiment, Simulation and Theory [15].

It is advised that computer simulation for the purposes of technology familiarisation include:

- Scientific principles that make the technology work
- Technology design
- Important design making for plant design
- Daily operations
- Preventive and breakdown maintenance
- Selected maintenance procedures

During the 18-24 months of fine-tuning operations and debugging the AI systems controlling the power generation technologies, computer simulation of the operations of the powerplants be made for the purpose of knowledge and skills transfer. This will also be relevant with changes in the plant owner's personnel because computer simulation can be used to familiarise new personnel with the operations.

3. Using International Resources through a Virtual Work Environment

When energy generation technologies are being adopted in a country for the first time and their design and manufacture is being done in another country, foreign consultancy is inevitable, whether for plant design and the establishment and even operations and maintenance. It can be costly to transport, accommodate and pay for foreign consultants to be present at the plant. However, nowadays due to fourth industrial revolution software, international resources can be accessed through a virtual work environment that can be used to establish a platform to investigate unfamiliar technologies that are essential to climate change mitigation in terms of energy efficiency and energy security. A virtual workplace is a workplace that is not located in any one physical space and not limited to any geographic boundaries [16]. Employees and management are connected via a private network or the internet and interact with each other via phone, Skype, cloud computing programmes and a whole host of other virtual options [16].

Unified Communications (UC), refers to the way different forms of communication tools in the digital workforce interact and collaborate (Fig. 7) [17]. By unifying phone calls, web conferencing, SMS, and email and other channels, users are able to share and access data and collaborate in real-time [17]. The right unified communications solution can take business processes to the next level, improving on collaboration, boost productivity, increase mobility and enhance the user experience [17].

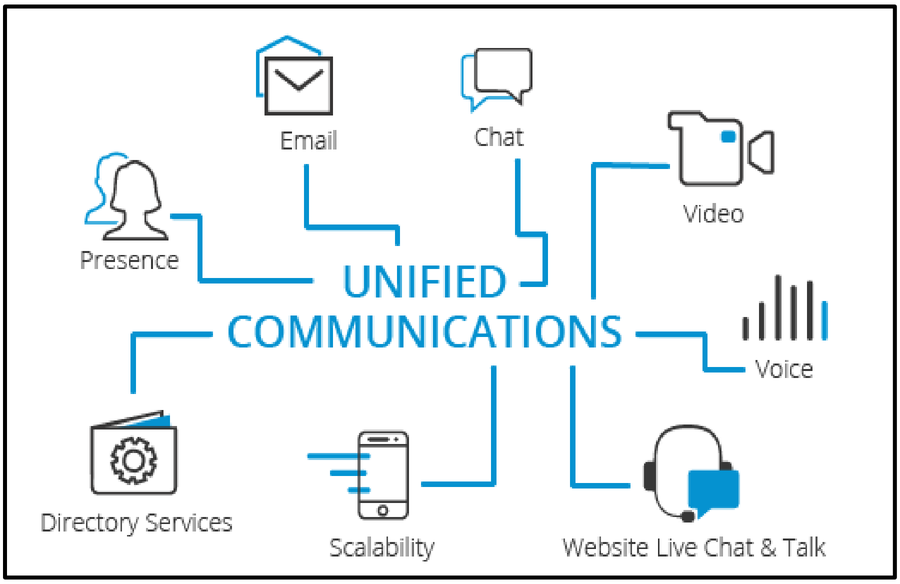


Figure 7: Virtual Work Environment [17].

Not only do the instruments of the fourth industrial revolution allow us to communicate with each other, but they also allow remote control of plant, equipment and processes. Internet technology allows companies to overcome many of the physical constraints that often prevent them from doing business in distant markets [18]. The issue of process control has been central in raising the productivity in industrial automation for years [18]. Remote control of processes is a new era which is presently supported by only a few companies, who are the giants of the automation industry [18]. Remote processing has a bright future, especially in the companies with many branches where electronically controlled machines are deployed as a part of the workforce [18]. While a computer connected to the automation devices can control and take data from processes at a production unit, the operator is able to process the data according to the rules and regulations and then issue commands necessary to control the system [18]. A schematic of a web-based monitoring system can be seen in

figure 8.

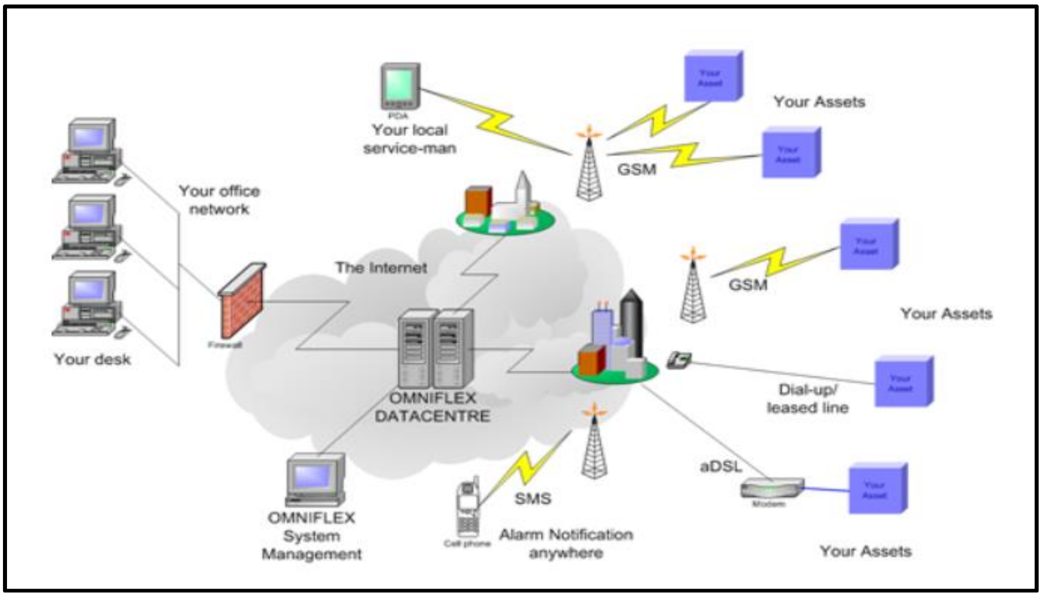


Figure 8: An Example of a Web-based Monitoring and Control System [19].

A computer connected to automation devices can control and store data from processes at a production unit. In the remote process control environment (REPCO) this process is done using a PLC connected to a server, which can be controlled via the internet by a user who is far away from unit, as shown in Figure 9 [18].

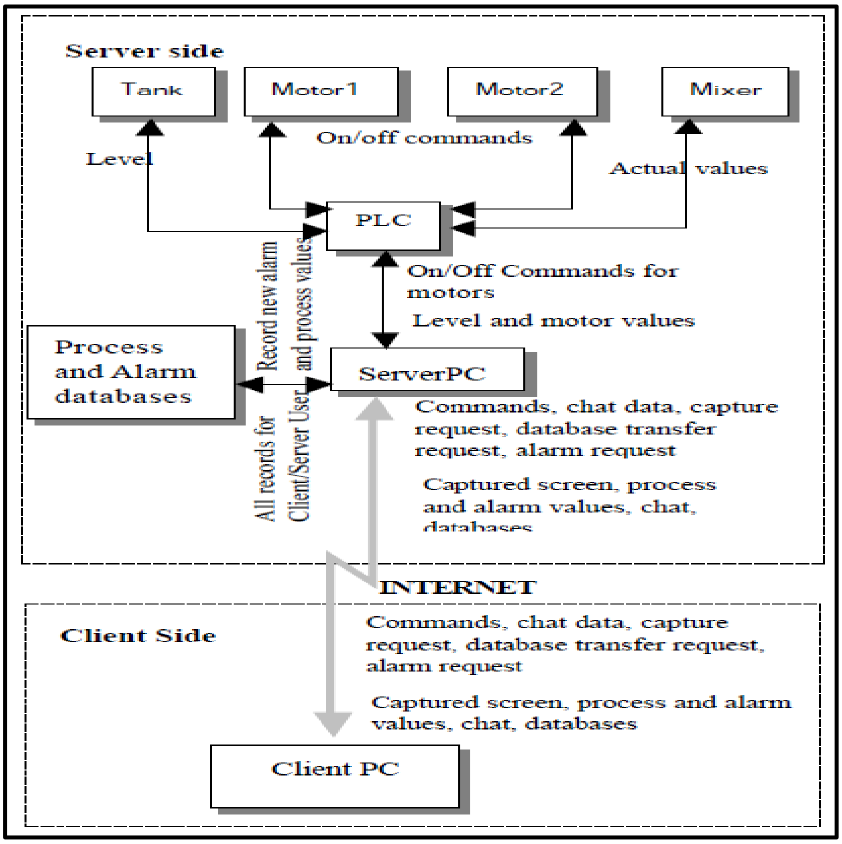


Figure 9: The Architecture of a Web-based System [18].

It is advised that web-based monitoring and control include:

- Plant control
- Troubleshooting and plant diagnosis capabilities
- Real time monitoring with SCADA
- Downloadable reports and records

This means that an organisation's workforce can be geographically anywhere and still perform their duties, especially where specific expertise is required and only available abroad. It will be cost effective to establish certain international consultancy relationships regarding specialised skills that can be operated remotely, except where physical work needs to take place and skills to perform the physical work are not locally available, in which case international personnel will have to be brought in.

4. Smart Electricity Grid

Having to coordinate multiple energy sources for a site is crucial in ensuring business continuity and reducing risks associated with business operations. In the fourth industrial revolution context, a smart grid uses advanced information and communication systems to connect power generators, distribution stations, and consumers [20]. Advanced data processing allows the processes of electricity distribution to be efficient, decentralised, flexible, reliable, and secure [20]. A smart grid also integrates the use of renewable energy sources into the existing power grid and creates microgrids to supply electricity demand [20]. A smart grid is an electricity grid which integrates the behaviour and actions of all entities connected (Fig. 10) [20]. There are three types of entities: generators, which generate electricity; consumers, which consume electricity; and those which can do both. These entities create a peer-to-peer network to ensure efficient distribution of the electricity, maintain low losses and a high level of quality, which maintains the security of electricity supply [20].

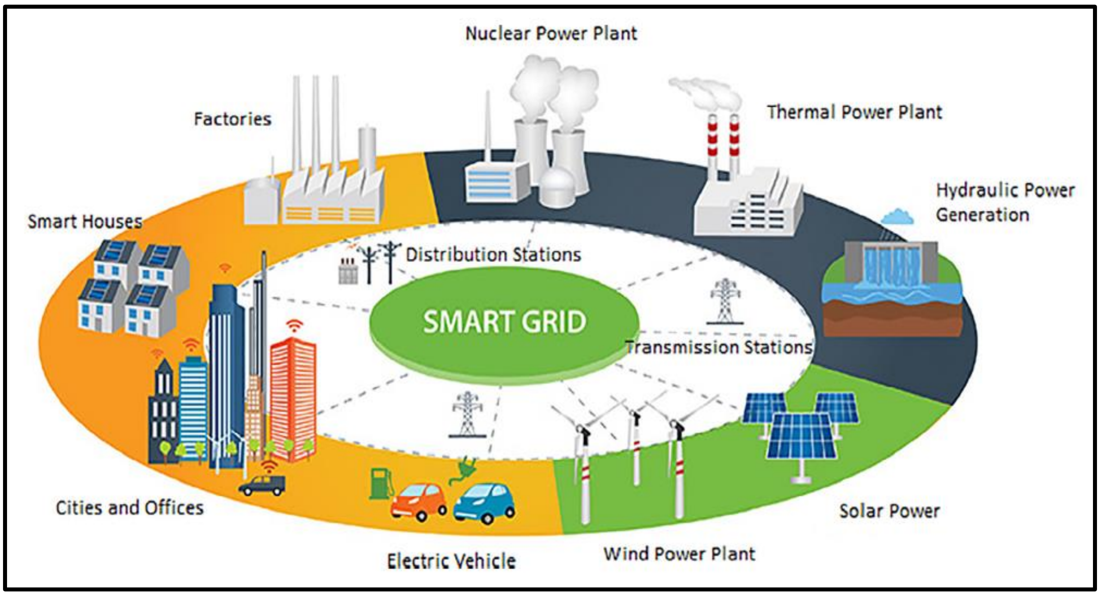


Figure 10: Smart Electrical Grid [20]. Smart Grids are Characterised by [21].

- Cutting edge applications, automation, efficient architecture, better management and standardised protocols

- Bi-directional communications
- Integrated with renewable energy sources and have wireless sensor networks

They have [21]:

- Demand-side energy management
- Intelligent fault detection
- Volt-var optimisation
- Wide-area early warning systems
- Integration of renewable energy sources into smart grids
- Microgrids as a normal feature in the overall grid system
- Integration of renewables in radial distribution networks via smart links
- Voltage based control of distribution generation units (DGUs)
- Active loads in smart microgrids
- Electric vehicles in a smart grid environment
- Low voltage, DC grid-powered LED lighting system with smart ambient sensor control in green buildings
- Multiple distributed smart microgrids with a self-autonomous, energy harvesting wireless sensor network
- Wireless sensor networks for consumer applications in the smart grid
- Wireless monitoring and control system for smart grids

Smart meters and sensors provide rapid two-way flow of data which allow both energy user and the generator to know exactly how much energy is being used at any given time. With a smart device, monitoring energy use is possible. The smart grid is a more reliable and responsive grid compared to our current one-way electricity grid between the electricity utility and customer. Power failures can be managed, and electricity restored at the push of a button. It is a more flexible grid that will be able to integrate renewable energy and electric vehicles into the network. This is part of a major transformation in the energy industry. The power is moving from the centre to the periphery of the grid. Previously passive consumers can become active participants in the network. Customers can become producers of power, feeding surplus energy back into the grid.

The potential support that the smart electrical grid can provide to coordinate and provide a smooth, uninterrupted and reliable energy supply in the process of transitioning to low carbon or carbon neutral energy supply, is attractive. Considering the airports in South Africa and their adoption of renewable and alternative energy [6], [7], [8], [9], [10], [11] in the journey towards carbon neutrality in electricity consumption, there is a need to coordinate the various energy sources for energy supply to the airport facilities. In terms of the principles of energy efficiency [22], principle one relates to the appropriate energy sources supplying the various energy needs (figure 11). In the transition, there will be a period of time where the energy demand for a facility or infrastructure will exceed the energy efficient energy source which means that

energy from another source will need to be brought online to satisfy the demand. For example, the ground heat sink may be exhausted and the chillers still require further heat rejection, or the solar heat or waste heat harvested from natural gas engines may not be enough to power absorption chillers for satisfying the cooling demand. At airports where wind energy and solar to electricity are adopted, cloudy days will decrease the solar photovoltaic plant electricity yield and wind energy will need to be used by the site. During these times the smart grid will need to work off an algorithm that will decide how to address the energy demand. The smart grid algorithm could (figure. 12 and figure. 13):

- use a load curtailment programme,
- employ another available power source to satisfy the demand or
- draw from stored power reserves.

The smart grid will be key to the success of energy supply from the airports' onsite energy mix. It will also enable selling energy to others and purchasing energy from others in the future.

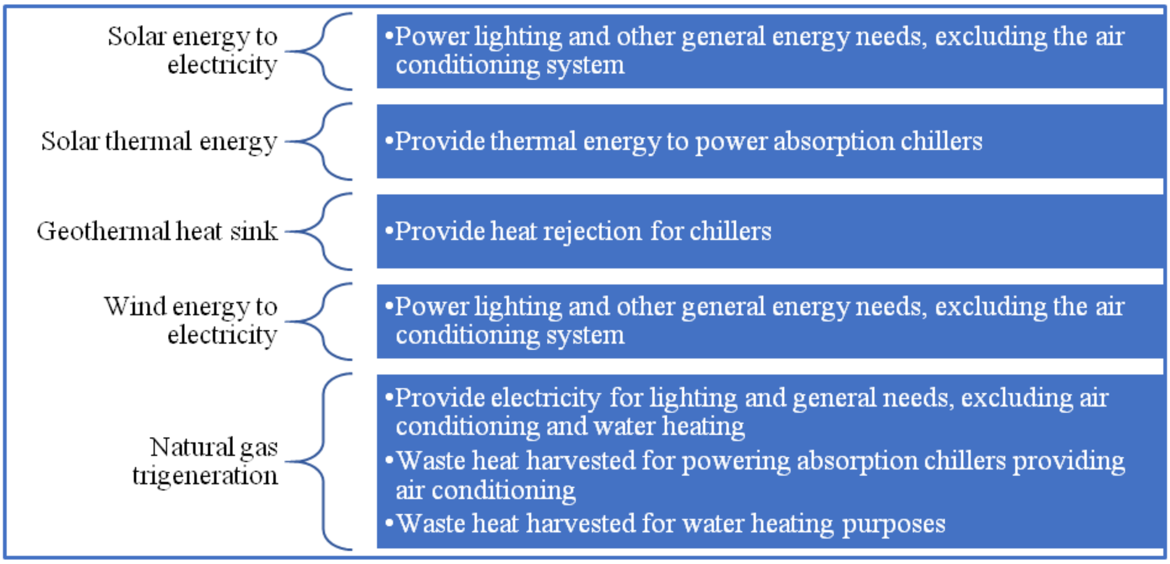


Figure 11: Efficiently Matching Energy Source to Energy need at Airports in South Africa.

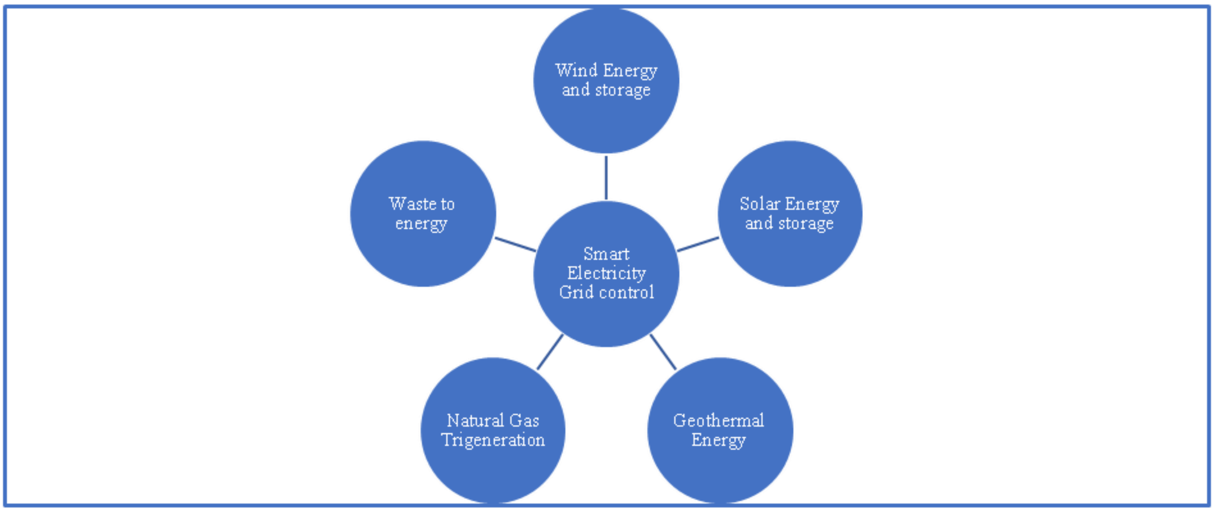


Figure 12: Smart Grid Concept for Cape Town International Airport.

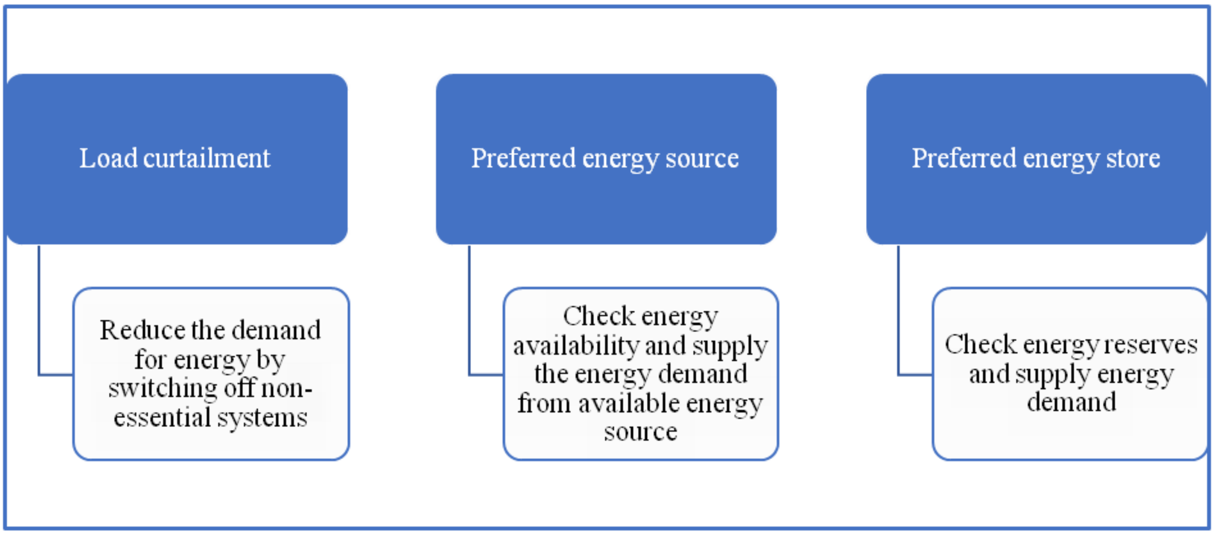


Figure 13: Typical Smart Grid Decisions for Supplying the Site Energy Demand.

5. Overcoming Energy Demand and Supply Mismatches

When energy supply exceeds energy demand there are usually no issues with respect to a smooth, uninterrupted power service, however, when there are instances or periods of time where energy demand exceeds energy supply, a short circuit will occur resulting in power interruption. Understanding the site's energy demand as well as the site's daily energy supply from the site's planned energy mix is crucial to identifying energy demand and energy supply mismatches. The energy generation plants can be capacitated accordingly, including energy storage where needed. The energy demand can also be engineered to coincide with the energy supply availability. Demand-side management (DSM) (figure 14) is a way to reduce peak load demand so that adequacy of electricity will be maintained without interruption [23].

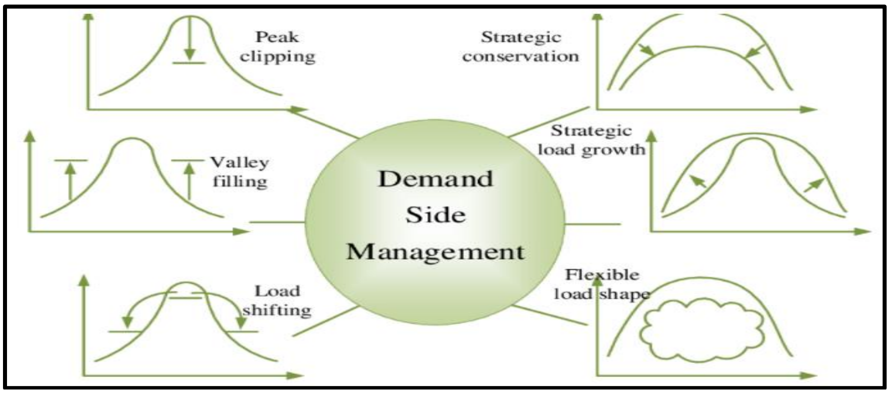


Figure 14: Demand side Management Techniques [23].

Some load levelling and load shifting techniques include:

- Thermal storage (ice storage) for air conditioning systems to reduce and or shift peak energy demand,
- Daylight harvesting to reduce daytime energy demand
- Controlling artificial lighting to specific lux levels
- Use of technologies that decrease demand for space conditioning

Most of the load levelling and load shifting techniques work through electronic control. Smart lighting systems can modulate lighting according to lighting demand and employing skylights and appropriate colours and materials of interior furnishing which will also reduce the lighting demand. Similarly, reducing solar heat gain by employing convective boundaries such as low emissivity glazing, an air-tight building envelope and insulation or heat deflective coatings on building roof will reduce space conditioning demand. Energy storage can be adopted for the storing of additional energy generation from renewable energy plants for use when needed. Other design interventions for chillers such as employing a standby vapour compression chiller when the thermal yield is insufficient to meet cooling demand, and employing electricity run evaporative cooling towers to satisfy additional heat rejection requirement, can be built in.

The energy supply can also be engineered to ensure efficiency through:

- Adequate plant sizing
- Plant modularisation for controlling energy yield
- Adequate and efficient energy storage media
- Matching energy type and energy demand efficiently and proportionally

Controlling the loading of natural gas engines so that yield meets energy demand efficiently through adequate modularisation is key to preserving fuel efficiency as well. Using the smart grid, selling off surplus energy could work well in terms of cost effectiveness and efficiency. Choosing the right energy storage medium and electronically controlling charge and discharge will preserve the plant against energy efficiency losses as well as ensuring that energy is available when needed.

CONCLUSIONS

This paper identified the four industrial revolutions and their key characteristics. Five areas where fourth industrial revolution instruments will be effective in overcoming barriers and challenges experienced by developing countries in achieving energy security and energy efficiency were explored. The use of AI to jumpstart the skills and competency shortfalls that will be experienced in maintenance, troubleshooting and operations of renewable and alternative energy plants was described. Another opportunity identified and explored was the value of computer simulation of renewable and alternative energy technologies to be used as a learning tool so that skills and competency can be transferred to the developing country's local workforce. To reduce costs as well as have access to skills and competency available abroad to establish renewable and alternative energy plants in developing countries, the potential of the virtual work environment including communication applications and web-based monitoring and control was presented. The smart electricity grid and its application in establishing an energy mix to serve a specific site was discussed followed by ways of overcoming energy supply and demand mismatches. This paper has established the usefulness and applications of the instruments of the fourth industrial revolution to enable and overcome challenges that developing countries may face when adopting renewable and alternative low-carbon energy sources.

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